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Experimental analysis of crack tip fields in rubber materials by 3D Digital Image Method

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Abstract

This paper presents the application of 3d digital image method to determine the crack tip fields in rubber materials. The in-plane displacement of crack-tip fields under Mode I loading is measured by using the digital moiré method and the out-of-plane displacement field near the crack tip is measured using the three-dimensional digital speckle correlation method. Basis on the in-plane and out-of-plane deformation distributions, a three-nested-deformation model is proposed to describe crack-tip fields in rubber-like materials with large deformation.

Keywords: crack-tip field; large deformation; three-nested-deformation model; digital Image method

1. Introduction

Increasing application of large-deformation materials, such as rubber-like materials and soft tissues, in engineering and biomedical industries, has made it important to maintain the reliability and stability of these materials. Their mechanical properties under fracture conditions should also be maintained [1,2]. In contrast to those of metals, the deformation and fracture properties of large-deformation materials are more complicated due to their geometrical and material nonlinearity properties, which make investigating fracture behaviors relatively difficult [3]. A few studies on crack-tip fields in rubber-like materials have been conducted. In terms of theoretical analysis, most researchers have focused on establishing constitutive relations to describe the large deformation in crack-tip fields[4-7]. On the other hand, material constitutive relations has not been evaluated by experimental analysis, because original and authentic displacement information on a crack-tip field can be obtained from experiments, providing useful insight for analyzing crack-tip fields. Thus far, however, few experimental efforts have been reported in the literature [8-10] studied the crack-tip fields under the Mode I fracture condition of a single-edged rubber sheet, whereas experimental investigation on crack-tip fields for their three-dimensional deformation is currently ongoing.

In this study, crack-tip fields under Mode I fracture conditions are investigated. The in-plane deformation of the crack-tip field is measured by the digital moiré method. The deformation characteristics and experimental sector

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division properties of the crack-tip field are analyzed based on the results of in-plane deformation. Furthermore, the out-of-plane deformation of the crack-tip field is measured using the three-dimensional digital speckle correlation method (3D-DSCM) [11]. Finally, using three-dimensional deformation fields as bases, a three-nested-deformation model is proposed to describe the deformation behavior of crack-tip fields in rubber-like materials with large deformation.

2. In-plane deformation field measurement by the digital moiré method

2.1. Digital moiré experimental method and Specimen

Digital moiré method is a full-field deformation measurement suitable for investigating problems with non-uniform deformation. It has the advantages of non-contact, real-time and high degree of measurement automation. In this paper, digital moiré method with circular and radial gratings was used to measure in-plane displacement fields near the crack tip of rubber material in polar coordinates [11]. There are three stages in applying this method: image preparation, image processing and result output, as illustrated in the flow chart Fig.1. For each step in the circular grating processing, the expressions describing the respective mathematical operation is shown in the flow chart. The corresponding expressions applicable to the radial gratings are similar to the horizontal grating processing and omitted in the chart for conciseness.

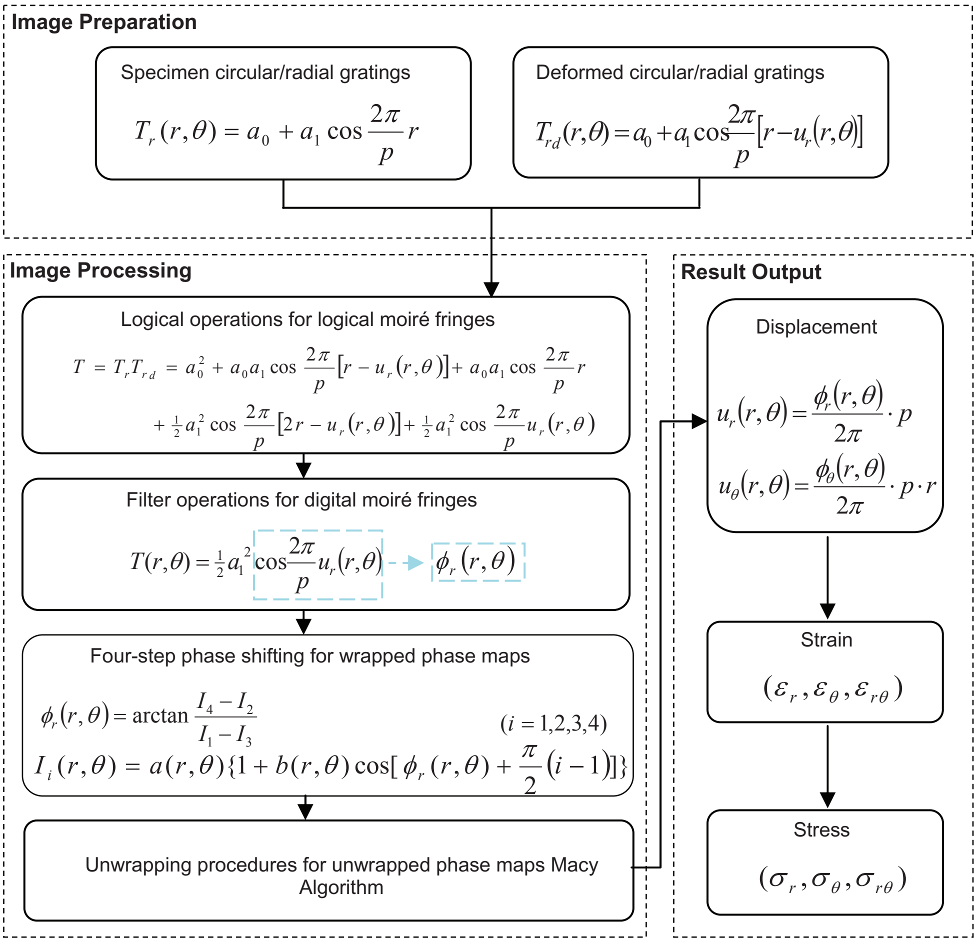

Fig. 1. Flow chart of digital moiré method with circular and radial gratings

The rubber disk specimen used in the experiment is shown in Fig.2. Its thickness is 2mm, and the efficient region is selected about 30mm in length and width. Initial cracks of 25mm in length were made double-edged. Specimen gratings were printed on the specimen surface tightly to assure the coherent deformation of the specimen and gratings [11].

Experiment were performed in an Instron3343 test machine and all tests kept a constant speed of 2mm/min for the grip and room temperature. Having applied the loading, the deformed gratings were captured by a CCD camera (Basler A202K with resolution of 1004pixel × 1003pixel) and shown in Fig.2.

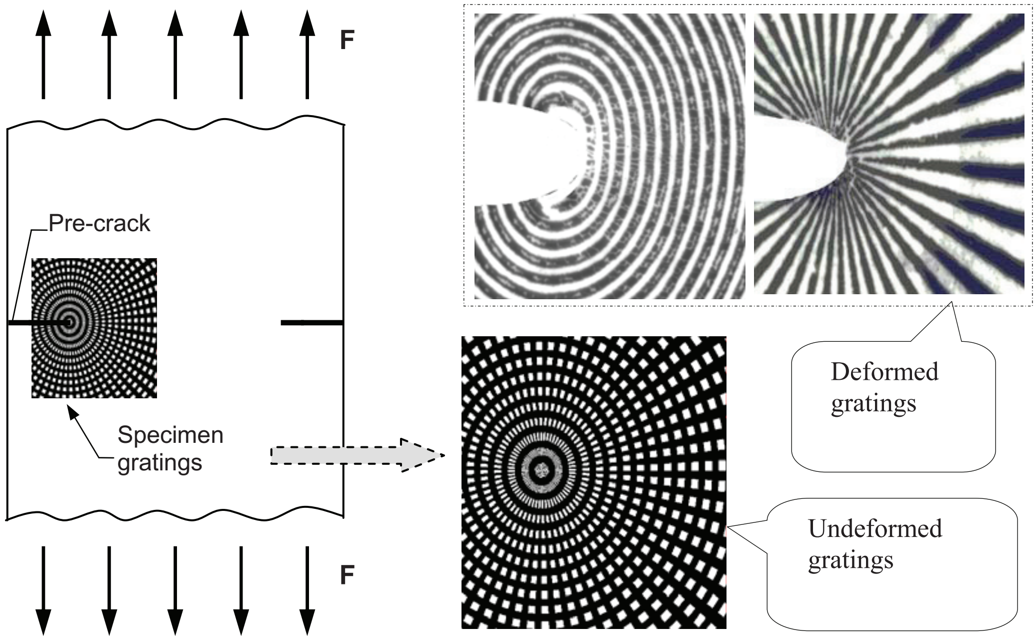

Fig. 2. Specimen and loading configuration sketch

2.2. Analysis of in-plane deformation fields

The full-field displacements in polar coordinates obtained in the experiments, i.e., the radial displacement u_r and circular displacement u_θ are investigated as follows. Fig.3 shows displacement fields under mode-I fracture condition by Digital moiré method.

It is observed from Fig.3 that characteristics lines with zero displacement and areas with same signs of displacement exist in both radial and circumferential displacement fields. The radial displacement u_r at a point represents the radial motion of the point relative to the crack tip. It contains the motionless lines B1 and B2 along which $u_r = 0$. These lines divide the crack-tip field into different regions. In the region EX, the radial displacement of the point moves toward the crack-tip, while in the region SH, all the material points move away from the crack-tip. Similarly, the circumferential displacement indicates the circumferential motion of a point around the crack-tip. The characteristics lines S1 and S2 with $u_\theta = 0$ separate the field into regions with clockwise and counter-clockwise rotations.

The features of deformation in region EX and SH are quite different for mode-I fracture. The region EX presents results of radial motion toward the crack-tip and circumferential expanding motion. In the region SH, the material points move away from the crack-tip and contract circumferentially. After loading, the region EX becomes wider and it occupies major areas surrounding the crack-tip, while the region SH shrinks and become narrower. The sector division frame facilitates the analysis and understanding of the crack-tip field for cracks in rubber or rubber-like materials under large deformation. With the sector division frame, a crack-tip field can be divided into distinguished expanding and shrinking sectors.

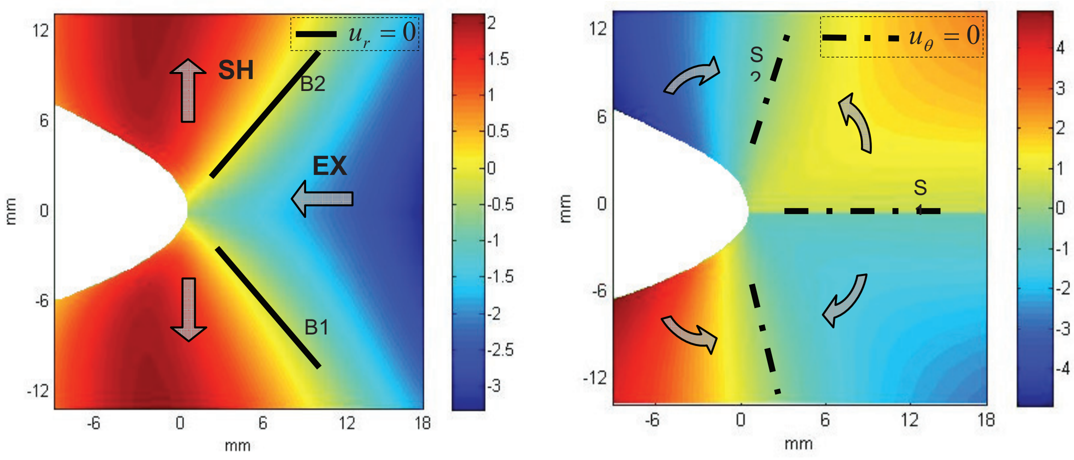

Fig. 3. (a) Displacement u_r of mode-I with 48N applied load (b) Displacement u_θ of mode-I with 48N applied load by Digital moiré experimental method

3. Out-of-plane deformation field by 3D-DSCM

It is necessary to consider the out-of-plane deformation in the crack-tip field of rubber material with large deformation due to the prevalence of three-dimensional stress in the local area. Three-dimensional digital speckle correlation method(3D-DSCM) is an effective extension of 2D-DSCM [12], which acquires three-dimensional surface displacement using a stereo pair of CCD cameras. Using this technique, the out-of-plane deformation field under mode-I fracture was measured in an experiment in which the specimen and loading configuration are the same as those in the previous in-plane deformation testing. Fig.4 shows a 3D plot of the deformed surface shape and the corresponding out-of-plane displacement field measured in a selected crack-tip region.

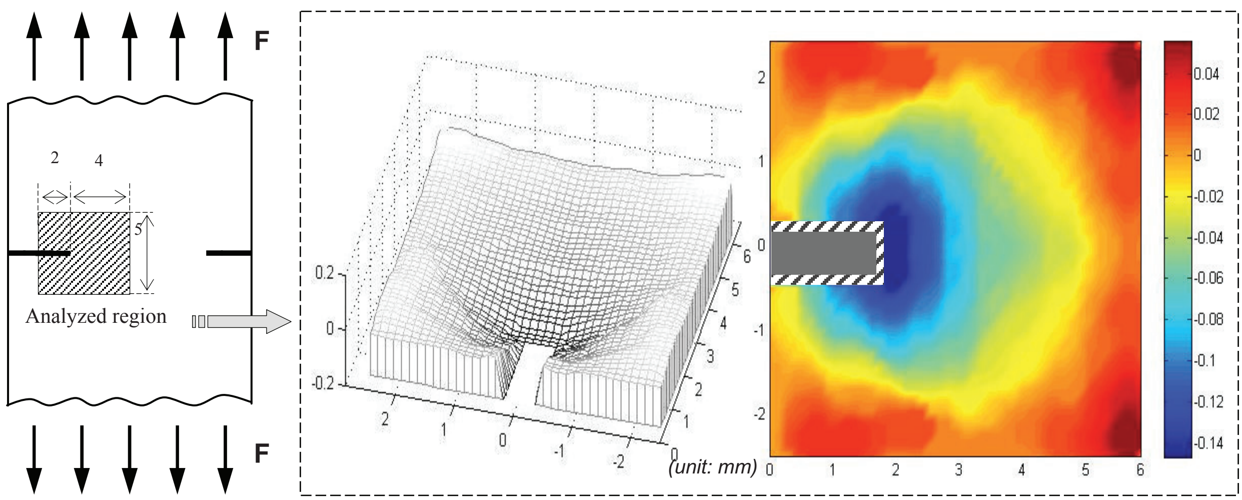

Fig. 4. Out-of-plane displacement field of mode-I fracture with 48N applied load

Apparently, the out-of-plane deformation occurred in the vicinity of the crack-tip, occupying an area of about 3mm in length along the crack from the tip. And the maximum strain of about 13% occurred close to the crack-tip, where damages may be caused due to a combination of large in-plane and out-of-plane deformation.

4. Discussion and Conclusion

The Crack-tip field in rubber material subjected to large deformation is investigates. Both in-plane and out-of-plane deformation fields are measured and discussed. It is testified that experimental results on sector division frame are consistent with the theoretical concept proposed by Gao, except for the new phenomenon observed. Based on the experimental results analysis, a three-nested-deformation model is proposed to characterize the deformation field of the crack-tip for rubber material with large deformation, as illustrated in Fig.5. Deformation situations of the crack-tip field can be described by three characteristic regions as follows:

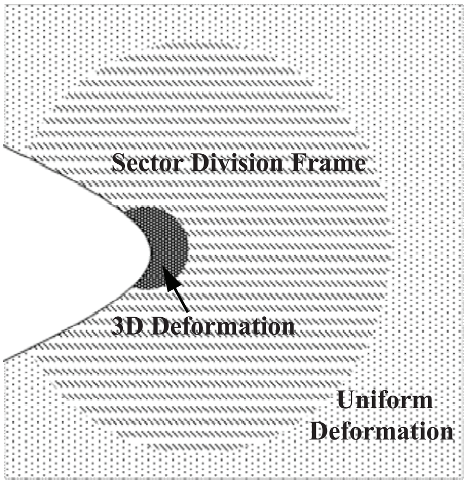

Fig. 5. Three-nested-deformation model and experimental sector division frame

- The inner region with three-dimensional deformation and possible damages, it occurs both in-plane and out-of-plane deformation, which may possibly produce damages;
- The interim region consisted of expanding sector and shrinking sector, the deformation characteristics are depicted by sector division frame. The region is divided into expanding sector and shrinking sector. Expanding sector is located perpendicular to the loading direction and shrinking sector is situated along the loading direction;
- The outer region with nearly uniform deformation.

Acknowledgements

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